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ORIGINAL PAPER

Defining the Boundaries of Development with Plasticity

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Abstract The concept of plasticity has always been present in the history of developmental biology, both within the theory of epigenesis and within morphogenesis studies. However this tradition relies also upon a genetic conception of plasticity. Founded upon the concepts of "phenotypic plasticity" and "reaction norm," this genetic conception focuses on the array of possible phenotypic change in relation to diversified environments. Another concept of plasticity can be found in recent publications by some developmental biologists (Gilbert, West-Eberhard). I argue that these authors adopt a "broad conception of plasticity" that is closely related to a notion of development as something that is ongoing throughout an organism's lifecycle, and has no clear-cut boundaries. However, I suggest that given a narrow conception of plasticity, one can define temporal boundaries for development that are linked to specific features of the morphological process, which are different from behavioral and physiological processes.

Keywords Development · EvoDevo · Modern synthesis · Morphogenesis · Norm of reaction · Phenotypic plasticity · Plasticity · Wallace's challenge

Developmental biology has deep roots in the history of the life sciences. Ontogenesis—how the living being appears and develops—has always been a major concern for life scientists and philosophers. In this rather old tradition, the concept of plasticity was first invoked in the intellectual context that tried to rehabilitate some sort of Aristotelism. Henry More (1614–1687) and Ralph Cudworth (1617–1688) refer to the notion of "plastic nature" as an architectonic force [that already existed in Aristotle (1999)] that explains the ontogenesis and the organization of living beings. By referring to plasticity, these authors want to propose an alternative to the mechanistic view of biological organization, developed by famous authors such as René Descartes (1596–1650) or Marcello Malpighi (1628–1694). Physical laws might not be the only way to explain the ability of living beings to produce new material from the previous generation.[1] Embryologists such as Caspar Friedrich Wolff (1734–1794) or Hans Driesch (1867–1941) try to determine the specificity of living beings compared to other natural beings. Morphogenesis thus becomes a field where the "plastic" ability to generate species-typical forms plays an important role. By contrast, a different use of plasticity has been emphasized by geneticists at the beginning of the twentieth century; this concept of plasticity is founded upon the notion of "norm of reaction," which depicts the "reactions of the genotypical constituents" in contact with various environments (Johannsen 1911, p. 145). The norm of reaction is itself understood as a synonym or a subtype of "phenotypic plasticity" defined as the ability to generate different kinds of form features within a species. More recently, a growing number of developmental biologists have referred to "plasticity" as a theoretical tool for evolutionary developmental biology (EvoDevo) (West-Eberhard 2003; Pigliucci 2001; Gilbert and Epel 2009; Pigliucci and Müller 2010). Some of these authors argue for a characterization of development as a process that "never stops," i.e., a process without clear-cut temporal boundaries (West-Eberhard 2003; Gilbert 2000/2010). These authors tend to equate

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[1] On this debate, see Duchesneau (1998).

the concept of "developmental plasticity" with the older concept of "phenotypic plasticity" that I will define in the first section of the article.

The main purpose of this article is to examine and discuss the facts and concepts about plasticity and especially its relationships with development. In the first part, I review the two very different research fields to study plasticity in the literature: genetics and development. Then I show how the genetic concept of plasticity has been extended in evolutionary biology, especially in the Modern Synthesis, leaving aside the developmental concept of plasticity. With the rise of EvoDevo, the distinction between genetics and development dissolves and a clarification of the meaning of plasticity becomes necessary. In the third section, I offer a clarification based on development and define what I call a broad conception of plasticity (BC-plasticity) and a narrow conception of plasticity (NC-plasticity). For BC-plasticity, development is not limited to the formation of morphological traits and includes the appearance of behavioral and physiological traits; however, for NC-plasticity, development is limited to the old conception of plasticity and includes only the formation of morphological traits. After formulating these distinctions and elaborating a precise description of these two conceptions of plasticity, I conclude in favor of the NC-plasticity conception for ascribing temporal boundaries to development. I demonstrate that BC-plasticity is weak, because it relies on a definition of development without any discernible boundaries, and then show that with a NC-plasticity conception of development we can identify temporal boundaries specifically linked to a definition of the morphological process.

Origins of Plasticity: Two Different Research Pathways

Although plasticity has received renewed attention in recent years, few reviews have studied this concept from a historical or theoretical point of view. Most of these reviews have focused on "phenotypic plasticity," defined as "the property of a genotype to produce different phenotypes in response to distinct environmental conditions" (Pigliucci 2001, p. 1). Like Pigliucci's definition as well as the "*norm of reaction*" concept that is the focus of the careful historical study conducted by Sahotra Sarkar (1999), the phenotypic plasticity concept is largely dependent on the rediscovery of Mendel's laws and the advent of genetics. Nevertheless, from a historical perspective, plasticity was used long before the emergence of genetics, particularly in embryology to refer to a propensity to generate species-typical form. The concept of "*morphological process*" reflects this type of plasticity. I highlight and distinguish these two concepts of plasticity by referring to the literature on the subject.

The Genetic Concept of Plasticity

According to Sarkar (1999), Richard Woltereck coined the term "*Reaktionsnorm*" in 1909 to explain Daphnia head-height differences after studying them in different German lakes, at varying nutrient levels. In order to depict the phenomenon, he drew some "phenotypic curves." He used the term *Reaktionsnorm* to indicate the totality of the possible curves. Some time after the rediscovery of Mendel's work (1900), he argued that what was inherited from one generation to another was this *Reaktionsnorm*. A few years later, Johannsen (1911, p. 133) endorsed the concept of reaction norm and argued that what Woltereck depicted were phenotype curves arising from the "reaction of the genotypical constituents" in contact with various environments (Johannsen 1911, p. 145). In Johannsen's view, a single phenotypic curve is a norm of reaction. In the US and in Europe (apart from the Soviet Union), Johannsen's distinction between genotype and phenotype became part of the standard picture of genetics. In this view, the constancy and the causal efficacy of the genotype will tend to minimize the complexity of genotype–environment interactions.

Whereas norm of reaction remained a relatively unused[2] concept in the West, biologists of the Soviet Union implemented a first experimental program that addressed the complexity of phenotypic variability (Adams 1980). In 1926, Vogt introduced two new concepts to describe the results of this program, expressivity and penetrance. "Expressivity" is defined as the extent of the manifestation of a mutation; "penetrance" is the proportion of individuals carrying that mutation, whatever the intensity of the manifestation of the trait. Sarkar (1999) explains that expressivity and penetrance have progressively been conceived as properties of a given mutation (and, eventually, the allele), rather than properties of a mutation relative to a constant genetic background (which they really are). From such a perspective, the predictable complexity in the genotype–environment interaction is erased. The purpose that the new notions serve is to maintain a genetic etiology in the face of the plasticity of the phenotype induced by genotype–environment interactions. Plasticity in the phenotypic manifestation of a trait becomes a result of a gene's expressivity and (indirectly) its penetrance. The purpose that the new concepts served was to maintain a genetic etiology in the face of phenotypic plasticity induced by genotype–environment interactions (Sarkar 1999). At the same time, in the Western world, Fisher (1918) and Wright (1920) offered almost equivalent methods to overlook the complex interaction between genotype and environment. In the statistical view, expanded after 1950, the heritability in

[2] However, as it appears in Leslie Dunn's book (1965), the notion of "norm of reaction" was known.

a broad sense (the individual heritability) is interpreted as the fraction of phenotypic variance that is due to genotypic variation. The interpretation is valid only if the interaction of genotype and environment is the same for all genotypes and all environments. In 1937, Dobzhansky introduced the norm of reaction to the Anglophone world to emphasize "phenotypic plasticity," a result of the complexity of gene-environment interactions leading to phenogenesis (Sarkar 1999). Referring to the example of a mutation in *Drosophila funebris* where the mutant phenotype does not manifest for generations after environmental modification (dry food), but may reappear when the offspring are supplied with moist food, he thinks that even if environmental factors induce a trait, it is an *unchanged* norm of reaction, which is inherited. Because of this specific interpretation of the reaction norm, and its progressive identification with the concept of phenotypic plasticity, plasticity became, for most biologists of the twentieth century, a notion of genetics (Schmalhausen 1949; Bradshaw 1965; Schlichting 1986; West-Eberhard 1989; Stearns et al. 1991; Scheiner 1993; Sultan 2000).

The Developmental Concept of Plasticity

More's (1659/2011) and Cudworth's (1678) metaphysical reflections about "plastic natures" have been pursued, a century later, on an empirical mode in embryology. Shirley Roe shows (1979) that Caspar Friedrich Wolff was, in the eighteenth century, at the origin of a renewed Aristotelian interest in epigenesis—the theory that an individual is developed by successive differentiation of an unstructured egg rather than by a simple enlarging of a preformed entity—and opposed to preformationism. To explain the organization of embryonic development, Wolff postulates the existence of an unknown force: the *vis essentialis*, which obeys laws of nature as does gravity or magnetism. In his book, *Theoria generationis* (1759), Wolff set out the reasons for which animals have a heart, while plants do not. He explains this phenomenon because animals' substance solidifies more slowly than the liquid of plants. Consequently, the motion of fluids, propelled by the *vis essentialis*, will only form parallel vessels in plants, while in animals, as the substance is much less quickly stiffened, branched vessels are formed. For Wolff, matter is not the passive matter defined by most preformationist theories in the eighteenth century. He describes a plastic concept of matter that possesses form, qualities, modes, and attributes and considers that not all matter is alike; through the qualities it possesses its nature is determined.

In the early days of experimental embryology, and nearly a century later, Hans Driesch (1867–1941) describes the egg during division as a "harmonious equipotential system." Each cell contains the latent potential (the plasticity) to produce a complete organism. Differentiation occurs because the forces that surround the blastomeres (early embryonic cells) vary according to differences in spatial and temporal positions of the original cells. Driesch is thus able to obtain a complete larva from four-cell stage blastomeres separated from the sea urchin embryo (Driesch 1928). By referring to the concept of "developmental potency," he is the first one to emphasize experimentally the idea of a plastic or dynamic property, internal to the matter (Dupont and Schmitt 2004). The progressive organization of the embryo is explained because of the specific properties and qualities of the matter and of the structure adopted. Influence of Wolff's thought is present in Driesch's work.

A few years later, Hans Spemann's (1869–1941) transplantations of cells or specific areas (e.g., the dorsal blastopore lip) from a *Xenopus* embryo to another reveal areas or cells that can develop normally after transplantation. A major step in embryology is made when Spemann and Mangold specify the concept of embryonic organizer (Spemann and Mangold 1924). Nowadays biologists define the process of "embryonic induction" as: "The mechanism that underlies the conversion of undifferentiated cells into the unique cells, tissues, organs responsible for the physiological functions of an organism" (Hall and Olson 2007, p. 103). With the spread of the cell theory, one of the great ambitions of embryology (Johannes Holtfreter; Ross Harrison; Viktor Hamburger) is to understand morphogenesis—the biological process that causes an organism to develop its shape—at the cellular level (Dupont and Schmitt 2004, chap 7). Progressively the observation goes from the whole organism to identify tissue, cell groups, and finally molecular determinants that appear to be decisive for the development of the shape. Since the late nineteenth century, morphogenesis has occupied a common field between genetics and experimental embryology (Morgan 1934; Waddington 1940) and progressively the study of morphological processes has tended to focus on the study of the genetic component of induction.

As I will demonstrate in the last section of the article, Stuart Newman, Gerd Müller, Isaac Salazar-Ciudad, and Ellen Larsen are the contemporary inheritors of the morphogenesis studies tradition. These studies focus on the particular life history of a species or organism. All the processes the developing organism goes through during its life cycle[3] are analyzed, and especially its progressive differentiation. Therefore, a particular attention is given to the dynamic, morphological processes that characterize the developmental mechanisms. Because of the influence of

[3] A life cycle is a period involving all different generations of a species succeeding each other through means of reproduction, whether through asexual reproduction or sexual reproduction (a period from one generation of organisms to the same identical stage).

the epigenesis theory on the study of morphogenesis, plasticity still refers for many biologists to an ability to generate different kinds of form features within a species across its life cycle. For these developmental biologists, plasticity is understood as a feature of morphological processes and as a property of organisms, and not as a property of the genotype–phenotype map.

Plasticity in Evolution

The Modern Synthesis brought together Darwinism, Mendelism, and population genetics in order to provide a powerful account of the mechanism of evolution. Therefore, the genetic conception of plasticity is strongly emphasized (Sarkar 1999). In the Modern Synthesis, the environment is seen most of the time as an external factor and is underestimated in the phenotypic change, in comparison with the genetic information. Indeed, the definition that affirms that "evolution consists of changing, within the collective genetic resources of populations, the frequencies of those genetic programs that lead to the successful development and survival of individuals under *prevailing environmental conditions*" (Dobzhansky and Boesiger 1983 [emphasis added]) is a verbose paraphrase of the statement: "Evolution is a change in the genetic composition of population" (Dobzhansky 1937/1951). According to this view, biologists consider an average environment in order to emphasize the role of mutations in the evolutionary process. The environment is a disturbing factor for the evolutionary analysis, so that mutation is the real cause of variation.

After the first success of the Modern Synthesis in 1950, development is considered, most of the time,[4] pointless in the study of evolution. It is almost 30 years later that some philosophers and biologists begin to reexamine the problem (e.g., Gould 1977; Coleman 1980; Hamburger 1980; Lauder 1982; Wallace 1986). Wallace (1986, p. 149) addresses what has become the main problem of EvoDevo's theorists: "Can embryologists contribute to an understanding of evolutionary mechanisms?". He argues that development is irrelevant to evolutionary explanations: "Problems concerned with the orderly development of the individual are unrelated to those of the evolution of organisms through time" (Wallace 1986). Two views in evolution can be separated. The first one focuses on organisms and sees evolution in the light of the vast array of morphologies one can find in nature; the second one focuses on genetic programs and sees evolution in terms of changing frequencies. Since the two views look incommensurable, Wallace refers to the well-known analogy of an optical illusion, an example used by psychologists: a sketch, where you might see in one moment an old woman, in the next a beautiful young lady, but at no time both images simultaneously. This analogy, if valid, suggests that biologists cannot see evolution with both views at the same time. Therefore, no synthetic view is possible. If we consider the distinction I previously put forward, does this also mean that a conception of plasticity that synthesizes the genetic and the developmental concepts is not possible either?

The appearance and growth, over the last 25 years, of EvoDevo, a new field of biology focusing on questions at the intersection of evolution and development, suggest that at least some developmental biologists have decided to take Wallace's provocative assumption as a challenge (Laubichler and Maienschein 2007; Sansom and Brandon 2007; Ioannidis 2008). Considering this position, a subsidiary question should be: could a unified concept of plasticity be considered as a key concept in the debate?

Some biologists try to answer Wallace's challenge by claiming that developmental biology and evolution are on the same footing (Hall 1999). For instance, Brian K. Hall argues: "Neither developmental nor evolutionary change can be explained by genes alone"[5] (Hall 2003, p. 220). Assuming this position, he focuses on the obvious distinction between the genes and the phenotype asking: "What components and processes lie between the inherited genotype and phenotypes?" Development is seen as the complex internal process—a "black box"—that receives inputs (genes) and produces outputs (phenotypes). Following this claim, a way to answer Wallace's challenge is to "unlock" (Hall 2003) the black box and to identify what is going on inside (analysis of the processes), in opposition to what is going on outside (analysis of the inputs and outputs).

Despite the quite simple and exciting promise offered by this proposal it is sometimes a thorny problem, even for these theorists, to make a clear distinction between what is going on in the black box and what is going on outside of it. And it is sometimes difficult to see if they are really investigating the black box itself or only its inputs and outputs. When Hall et al. (2004) suggests that the inherited genotype includes the phenotype of the genes itself (proteins), the one-to-one relationship between a single genotype and a single phenotype appears compromised and development—as the ontogenesis of the adult phenotype—is not anymore the only process included in the black box. Signal transduction, transcription regulation, and processing must also be included as processes (Larsen 2004).

[4] It was "pointless" in the Modern Synthesis but with the exceptions, by no means insignificant, of the famous work of Waddington (1940), Lerner (1954), or Schmalhausen (1949).

[5] This assumption constitutes the real focus of most of the EvoDevo studies, more than the origin and the nature of change in life, whether it be developmental or evolutionary.

It has been increasingly acknowledged that development cannot be reduced to a genetic program yielding a phenotype. A new account of the "environment," and its relationship to the developing organism, is at the root of the change. Whereas the environment is seen most of the time, in the Modern Synthesis, as an external factor and is underestimated in the phenotypic change, it has become in this last decade a main factor in the establishment of the phenotypic novelty. In the "new introduction"[6] to his article "Gene, Organism and Environment," Lewontin argues:

> The changes that occur in an organism during its life from conception to death depend uniquely on both the cell constituents that are present in the fertilized egg and on the sequence of environments through which the organism passes in its lifetime (2001, p. 55).

The environment is no longer composed solely of the external environment, it involves both an internal or "somatic" environment (Buss 1987) that includes the product of the genes, the cellular types, the temperature, etc., and an external, "ecological" (Williams 1996)[7] or "extrasomatic" (Buss 1987) environment that includes more or less the physical environment, the biotic environment, or even the social environment. Some recent works have paid more attention to this broader environment (Hall et al. 2004; Gilbert and Epel 2009) and its interaction with genotype during development. As a result, what was previously considered as a "part" of the black box has now become a new type of input.

This new type of input has been emphasized through the recent use of the concept of "developmental plasticity." The concept is borrowed from neural and behavioral biology to emphasize the processes resulting from the genotype–environment interaction and leading to phenotypic plasticity (what we have called the "genetic conception of plasticity"). According to Scott Gilbert, developmental plasticity "makes it possible for environmental circumstances to elicit different phenotypes from the same genotype." The author adds: "Many species have a broad *reaction norm*, wherein the genotype can respond in a graded way to environmental conditions" (Gilbert and Epel 2009, p. 11[8] [emphasis added]). Therefore, this definition, in a textbook on development, probably sheds a new light on the types of interaction between the different inputs on the black box. These inputs are no longer limited to the genetic information. They involve different types of genotype–environment interactions, or input interaction. The genetic conception of plasticity is investigated in a new way.

In 2003, a collection of papers edited by Susan Oyama, Paul Griffiths, and Russell Gray, *Cycles of Contingency: Developmental Systems and Evolution,* was published. This book puts forward a new theoretical framework baptized "developmental systems theory" (DST), which aims, among others things, to emphasize the relevance of development in evolution. In a developmental system, every trait is produced by the interaction of many developmental resources. The gene/environment dichotomy is considered as only one of the many ways to divide up these interactants (Oyama et al. 2003, p. 2). The system is defined as the sum of the interactants and processes that produce a life cycle (Oyama et al. 2003, p. 214). The new framework of DST introduces the assumption that development never stops during the life of organisms and that it is a general process of a life cycle. Based on this assumption, a connection can be drawn between this definition of development in terms of life cycle and the concept of developmental plasticity, defined by Gilbert (2000/2010) as the manifestation of any genotype–environment interaction (both internal and external). Consequently, no significant distinction is made between the interaction of inputs (what is going on outside the black box) and processes (what is going on inside the black box). Thus, a "developmental system" could also be called a "plastic system," which puts emphasis on the interaction of inputs rather than on the processes themselves. In this framework the cessation of interacting inputs, which corresponds to the end of development, is death.

Investigation of evolution with developmental biology has led to an apparent merge between the two concepts of plasticity (the genetic and the developmental) into a single broad concept of plasticity (that I call BC-plasticity). At the same time, the broader definition of the environment has induced a new understanding of development that includes both morphological, behavioral, and physiological trait formation. As a result, developmental biologists have concluded that the temporal boundaries of development correspond to the death of the individual and that the organism never stops developing during its life. In a sense, this hypothesis might be confirmed if no distinction should appear between the new developmental use of plasticity (in

[6] The article "Gene, Organism, and Environment" by R. C. Lewontin (2001) first appeared in Bendall (1983), but the quotation is from a "new introduction" to this article that Lewontin produced specially for the book *Cycles of Contingency: Developmental Systems and Evolution*, pp. 55–57.

[7] Williams refers to the old external environment with the notion of ecological environment to contrast with the internal environment of the organism considered (Williams 1996).

[8] The quotation is originally from Scott Gilbert (2000/2010), *Developmental Biology,* 6th edn, chap. 22. In the later editions of the book this chapter disappears but becomes part of his new book with David Epel (2009).

the BC-plasticity) and the old developmental conception of plasticity (as a feature of morphological process). Several reviews suggest that a polysemy of the notion exists (e.g., Pigliucci 2001; see also Fusco and Minelli 2010), and the observation that such a polysemy often appears in a single study suggests that a merge between the two understandings is not possible.

For instance, in *Phenotypic Plasticity: Beyond Nature and Nurture*, Massimo Pigliucci (2001) refers to several experimental demonstrations of developmental "windows of plasticity." He shows that the plasticity of an organism depends on the traits and environments considered (inputs), but also on the timeframe during ontogeny when those environments are experienced (processes). Jason Hoverman and Rick Relyea (2007) demonstrate the existence of a "developmental window for trait induction" in some species of freshwater snails (*Helisoma trivolis*). They discover that snails form morphological defenses against water bugs (thick shell) and possess a developmental *window* for inducible defenses. This observation implies that phenotypic plasticity may itself be considered as flexible or plastic. Indeed, the ability to produce different phenotypes (the genotype–environment interaction) may change quantitatively depending on the period of the life. And therefore, any input interaction may not be the same during all the life of the organism (*variability* of the input interaction over time). Note that the expression "window of plasticity" suggests that some temporal boundaries exist. If one considers the correlation between plasticity and development (implicit in the BC-plasticity), then if there is a "window of plasticity," one wonders what happens outside this window. Do we have less plasticity or an absence of plasticity? Is it possible to say that there is an absence of development outside the window? If so, the thesis that considers extended development, without clear-cut boundaries, based on BC-plasticity, seems weak. Therefore, we can reconsider the question of where to put the temporal boundaries of development.

I have shown in this section that two conceptions of plasticity can be distinguished: a BC-plasticity that includes both genetic plasticity and developmental plasticity, and does not focus exclusively on the formation of morphological traits; and a NC-plasticity that includes only developmental plasticity, and focuses exclusively on morphological processes. With BC-plasticity, development ends with the death of the organism and starts with the first inputs leading to a phenotypic expression. For example, Hoverman and Relyea (2007) suggest moving away from studies that focus on a single point in development (a single developmental stage representative of any developmental process) and suggest looking at the entire life cycle. I argue that more specific attention to the NC-plasticity allows us to look at the entire picture and to pay more attention to the developmental process, instead of focusing mainly on the input interaction. This perspective could lead to a broader understanding of the developmental processes.

In the last part of this article, I focus on the consequences and meanings of adopting a particular conception of plasticity for the domain of data studied, the type of representation and the experimental tests and quantification used. The comparison between the two conceptions, based on these aspects, will help us to see in which case the boundaries of development appear more clearly.

Toward a Clarification: Linking Plasticity and Development Together

The differences between BC- and NC-plasticity are based on: (a) The data access: BC-plasticity is depicted in a law-like way whereas NC-plasticity implies a comparison between different periods of the life cycle; (b) The representation of plasticity: *X* and *Y* axes differ in each case depending on whether the organism's life is included as a parameter; (c) Experimental tests and quantification: An examination of how plasticity is tested in both cases and how we may quantify the amount of plasticity is another fundamental way to distinguish between the two conceptions. These comparisons will allow us to make conclusions about the most suitable conception of plasticity for studying the boundaries of development.

BC-Plasticity

Most of the recent studies in biology refer to this BC-plasticity. Many analyses have been made on the importance of environment-development interactions. Van der Weele (1993) makes a distinction between three schools of thought regarding these interactions: the classic *Neo-Darwinian approach* (gene-centric-view: the genetic program is central to an understanding of development, and environmental effects are background noise to be minimized); the *internalist approach*: the development is determined more by the internal environment (environment of the cell and cell–cell interactions opposed to the external, biotic or abiotic, environment), than by genes; and the *constructionist approach* (which sees the external environment as the dominant player in a continuous interaction with the genotype). Nevertheless, even if these three schools of thought look different with respect to the importance attributed to the factors involved in the interactions, none of them takes into account the variations of the environment-genotype interaction *during lifetime*. In the BC-plasticity, plasticity is understood as a general process, and biologists attempt to describe it in a "law-like" way, as opposed to a historical way. For instance, the authors of

DST suggest that a set of themes helps to depict developmental systems (Oyama et al. 2003, chap 1). But, in a sense, we can say that these themes determine also the developmental system. So even if "contingency" is one of these themes, it will be captured in the concept of the "developmental system."

I suggest that the BC-plasticity is coherent in a context of a life-cycle perspective (see Minelli 2011), where all types of interactions linking the inputs with phenotypes are defined as plastic processes. Development is considered to be a result of these kinds of interaction and, for this reason, the boundaries of development depend on the presence of the input interactions.

Data Access

In most of the studies, plasticity is described for a given phenotypic trait and concerns intraspecific environment–genotype interactions. Because of their notable stability[9] ("Mean phenotypic value" in Fig. 1), the animal models usually described in developmental biology—such as *Drosophila,* Zebrafish*,* frog or sea urchin—are not the kind of organisms depicted in phenotypic plasticity studies. In these studies, species for which the external environment plays an important role are emphasized (e.g., the sex ratio of reptiles depending on temperature, the patterns and colors of butterflies depending on season). Animal models systems have been criticized for not being representative enough of the broad majority of the animal kingdom (Bolker 1995). This same criticism might be addressed to the studies of plasticity (e.g., Brakefield et al. 1996; Nijhout 1991; Pener 1991). The specificity of the models emphasized prevents us from having a generalized view on the different mode of interaction of the genotype with the environment and suggest that the mode of interaction is unique. If the input interactions are considered in general, that is, without distinction between them over time, then, only one type of boundary for development, which is equivalent with "no interaction," might be considered. If the differences between the processes (interactions throughout life) are emphasized, different types of boundaries for the development might also appear depending on the features of these processes.

This observation leads us to another important feature of BC-plasticity studies: the referential time scale. If any, it is mainly an evolutionary one (Bradshaw 1965; Schlichting 1986; Sultan 1987; West-Eberhard 1989; Scheiner 1993; Schlichting and Smith 2002). The phenotypic change, over time, is only considered from an evolutionary perspective and, if not, comparisons in the rate of plasticity during life are seldom detailed. In this broad conception, plasticity looks like a constant physiological process during the life of organisms. For this reason, it may be compared to other regulatory processes including both physiological and/or behavioral mechanisms. Piersma and Lindström (1997) argue for a connection between physiological plasticity, behavioral plasticity, and developmental plasticity, referring for instance to organs' size change over short periods of time (e.g., organ adjustments during lactation or migration-related changes in the digestive system). In this perspective, it looks like development lasts all life. More recently, biologist Mary Jane West-Eberhard (2003) has emphasized this connection in a more general way. In *Developmental Plasticity and Evolution,* she develops a general theory in an attempt to frame the entire question of phenotypic novelties, based on the statement that "a fundamental quality shared by behavior and development is condition-sensitivity: both are partly directed by circumstances" (West-Eberhard 1992). West-Eberhard introduces a broader notion of developmental plasticity, in order to demonstrate the range of the underlying mechanisms of input interaction. West-Eberhard's main purpose is to draw a link between development and behavior. Therefore, the conception of plasticity implicitly reinforces the role of the inputs (condition-sensitivity) but it leaves our understanding of the process unchanged. Plasticity is defined as "input interaction," meaning whatever variations might appear during the life of the organisms. The domain data for the BC-plasticity emphasizes the homogeneity of a developmental process, understood as the result of any input interaction. The temporal boundaries, if investigated, will rely on the existence of such interaction. However, as I will show in the next section, the BC-plasticity is faced with some significant problems.

Representation of BC-plasticity

This representation (Fig. 1) illustrates the confusion that exists in the BC-plasticity between the different meanings of plasticity. Plasticity is both represented by the slope of the line (here called "developmental plasticity") and the line itself (here called "reaction norm"). This type of representation is found frequently in published reports, mostly as an artifact, result of an experimental device to show the variation (e.g., Pigliucci 1997). In any case it highlights the genotype–environment interaction and its phenotypic result. In the BC-plasticity, any input interaction is interpreted in developmental terms. Indeed, comparisons between different reaction norms during the same life cycle are rarely made. Therefore, through this representation, development doesn't appear as a process with temporal boundaries but as a general property of living beings.

[9] In 1985, one conclusion and recommendation of the National Research Council (United States) concerning the models for biomedical research was, among other things, to favor genetic uniformity of organism, where applicable (NRC 1985, p. 73).

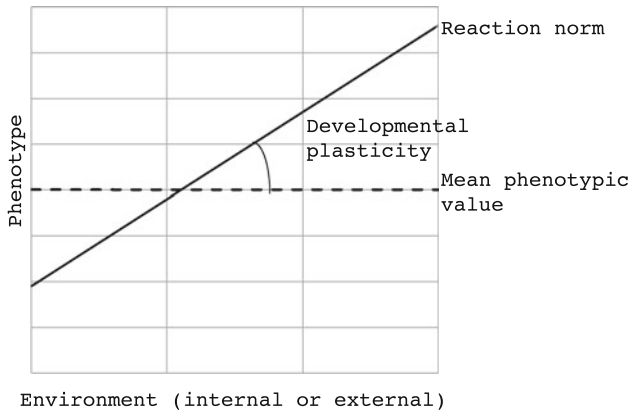

Fig. 1 Representation of BC-plasticity including both the reaction norm (*the line*) and developmental plasticity (*the slope of the line*)

Experimental Tests and Quantification

It appears, considering the representation above, that BC-plasticity is tested in taking into account "the array of phenotypes that will be developed by the genotype over an array of environments" (Gupta and Lewontin 1982). The notion of "phenotype" as defined by Mary Jane West-Eberhard (2003, p. 31) is exactly the same as the one introduced by Johannsen (1911), for the first time, to describe the genotype–phenotype distinction: "The phenotype includes all traits of an organism other than its genome." In the life-cycle perspective, an organism is usually depicted as in an endless cycle of temporary phenotypic forms. Individual life cycles are also connected—some phenotypes are inherited from the previous generation through the egg cell—and this points out cross-generational phenotypic continuity. However, with this conception there is no clear-cut boundary to the development, not even death. In this conception, development is synonymous with evolution. BC-plasticity brings together these cross-generational phenotypes. The implicit link between these phenotypic expressions is depicted by the notion of *interchangeability*: "Phenotypes responsive to the environment can make them [also] responsive to inputs specified by genes, to manipulation by parents and parasites, and to internal interactions among parts […]. *Responsiveness* to all of these different influences gives rise to development […]" (West-Eberhard 2003, p. 93 [emphasis added]). A change in one environmental component (internal or external) may give rise to a plurality of phenotypes. This phenomenon is represented by the reaction norm (Fig. 1), which is a property of the genome and can also be selected. Because plasticity is not a synonym but an attribute of the reaction norm, different genotypes are expected to differ in the direction and amount of plasticity that they are able to express (Gotthard and Nylin 1995; Via et al. 1995). But most of the time a reaction norm is only seen as a type of plasticity. Consequently, development is considered as a result at the phenotypic level of plasticity. But by development as the sum of the input interactions during life, the BC-plasticity is not able to delineate any clear-cut boundaries.

NC-Plasticity

Having described BC-plasticity and its consequences for the boundaries of development, the aim of this section is to propose another conception of plasticity that we call "narrow conception" (NC-plasticity). Indeed, I suggest that some features of the developmental process are not depicted with the BC-plasticity. In order to show the differences between the two conceptions, the same criteria used to describe BC-plasticity are now used to analyze the NC-plasticity: the data access, its representation, and the experimental tests and quantification.

What I call NC-plasticity refers to the developmental conception of plasticity that I described in the first part. This conception is linked to ontogenesis. Contrary to BC-plasticity, NC-plasticity focuses on development as a historical process and on morphology as the *change over time* of input interaction. Developmental boundaries depend no longer on the existence or absence of input interactions but on the existence or absence of the change, over time, of the input interactions, and so on the processes.

Data Access

Contrary to the broad conception, NC-plasticity relies on morphological plasticity (usually irreversible) as opposed to behavioral plasticity, which is considered as similar and an addition to physiological plasticity. The latter is manifested for example in plants' alterations of photosynthetic rates in response to light availability and mammals' changes of respiration rate or production of red cells in response to alterations in oxygen availability (Cavalli-Sforza 1974). The former is manifested in limb development and suggests an irreversible change. Very few studies deal with this distinction and some of them are not really clear on their purpose. For instance, Diggle (1993, 1994) establishes in his studies on *Solanum hirtum* that sex determination depends not only on plasticity to resource[10] (reaction norm), but also on the developmental architecture of the plant (morphogenesis). Floral sex is underdetermined until the floral buds reach 9–10 mm in length. If the buds are developing in a basal position, they turn into hermaphrodite flowers regardless of the environmental conditions. Diggle termed this dependency of plasticity on the previous developmental

[10] Access to the resources is artificially increased or decreased (see Diggle 1994).

history of the organism "ontogenetic contingency." This experiment implies that sex determination in *Solanum hirtum* can't be explained with a simple reaction norm or in looking at input interaction (BC-plasticity). A timescale must be introduced. This timescale is based on the idea that development might be considered as a "historical rather than a programmatic [or law-like][11] phenomenon;" furthermore, "Each stage in the progressive structural and compositional reshaping of the embryo is both the effect of earlier and the cause of later developmental transactions" (Stent 1985, p. 1). With this temporality it is possible to describe the establishment of a "developmental architecture of the plant" or a "window of plasticity" (NC-plasticity), in the case of the freshwater snails mentioned previously.

BC-plasticity focuses on hypothetical alternatives between different phenotypes, whereas NC-plasticity aims to bring in the same picture different phenotypes expressed over time by the same organism. If we consider this temporal perspective, the question is: When does the morphological process end? The study of NC-plasticity, understood as the variation of the input interaction over time, may give an answer to this question. The temporal boundaries of development depend on the end of plasticity understood as a feature of morphological process.

Representation of NC-Plasticity

In the NC-plasticity's representation (Fig. 2), the *X*-axis and the *Y*-axis are different from the previous representation (Fig. 1). A time scale is introduced and the genotype–environment (input) interaction corresponds to the *Y*-axis. Therefore, the variation of the input interaction appears over the lifespan. I suggest that plasticity, as a feature of morphological process (NC-plasticity), represents the change of this input interaction over time. Development ends when variability of the interaction stops. The first two parts of the diagram could be applied to some multicellular organisms but not the third part. The first part represents variation of the interaction over time (cascade of chain reactions); the development ends when the "adult stage" (second part) starts, where the interaction remains constant, keeping the organism in equilibrium. "Phenotypic plasticity" can be identified during this second stage. Some organisms may express another "wave" of morphogenesis if a new wave of variation in genotype–environment interaction appears. Some organisms may never express such variation in their genotype–environment interaction during their life. We will detail in the next section what this "wave of variation in the genotype–environment interaction" means.

[11] Addition is mine.

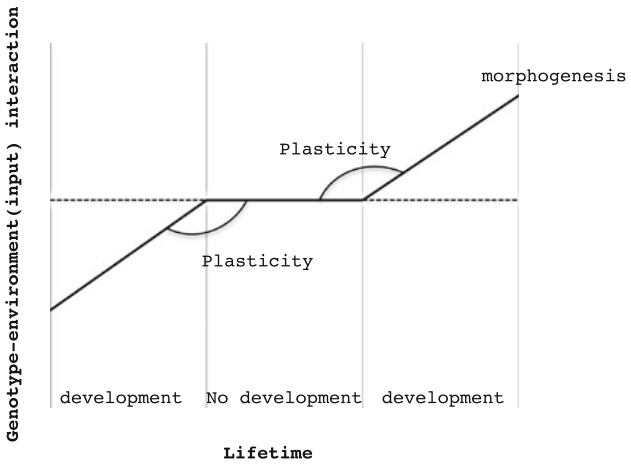

Fig. 2 Representation of NC-plasticity as a feature of morphological process, understood as the variability of genotype–environment (input) interaction during the lifetime

Experimental Test and Quantification

Few studies are devoted only to NC-plasticity compared to BC-plasticity. However, some very interesting studies, dealing with this issue, have been developed recently (e.g., Salazar-Ciudad et al. 2003; Forgacs and Newman 2005). These studies investigate the specificity of morphological processes compared to behavioral and/or physiological processes. They focus on the transition levels for biological organizations. These specific periods, which can be expressed during the life of some species, correspond to a change in the mode of interaction for the genotype and its environment. If one considers a cascade of molecular events (chain reaction) over time, there is a high degree of plasticity. It is not a result of the amount of input interaction (BC-plasticity) but it is a result of the quick change, over time, of the input interaction that will lead to the appearance of emergent properties,[12] understood as a feature of morphological process (e.g., cell polarity, epithelial folding) (Newman and Bhat 2008). These emergent properties lead the developing organism into different states (e.g., from unicellular to multicellular, from multicellular uniformity to multicellular heterogeneity). In this conception, development would start with the first expression of an emergent property and would stop when equilibrium is reached, when environment–genotype interaction stops changing so quickly over time (Salazar-Ciudad et al. 2001). Some evidence seems to support this assumption.

[12] Emergent entities (properties or substances) arise out of more fundamental entities and yet are novel or irreducible with respect to them. The new entities are more than the sum of the parts they are composed of. In the case of multicellular organisms, cellular properties are not the simple result of the sum of the properties of the individual cells.

Table 1 Distinction of the two conceptions of plasticity and consequences for the developmental boundaries

	NC-plasticity (narrow)	BC-plasticity (broad)
Definition	Developmental conception of plasticity as a feature of morphological process	Phenotypic plasticity + developmental plasticity (as physiological plasticity and/or behavioral plasticity)
End of development = end of plasticity	End of morphological process	"Development never stops" (Gilbert S) Death
Biologists	Larsen E, Newman SA, Salazar-Ciudad I, Müller G	Gilbert S, Lewontin R, West Eberhard MJ
Theories	Historical conception of development (Stent GS) Distinction of physiological plasticity and behavioral plasticity with morphological plasticity (Cavalli-Sforza LL)	Law-like conception of development: DST (Oyama S, Griffith PE, Gray RD) and life-cycle theory "Developmental plasticity theory": (West-Eberhard MJ)

In a paper from 2003, Salazar-Ciudad et al. show that cell differentiation may equilibrate faster than cell movement (see Laplane 2011). Molecular and physical interaction effects may not have the same consequence whether physical equilibrium is reached or not. Forgacs and Newman (2005) examine the case of limb morphogenesis. They depict two-dimensional simulations to show the "robustness" of embryonic limb development. These simulations emphasize the boundaries of limb development ("when the equilibrium is reached") and the role of developmental constraints. For instance, in the pattern of cleavage, constraint is the distribution of yolk, a dense and viscous material; in the cell shape, constraints are linked to the incompressible nature of the liquid drop—its volume is constant while its shape can change—and to gravity. In other words, developmental constraints correspond to some associations of particular physical, genetic, and chemical constraints. They show that "active cell movement characterizes early morphological process" (Forgacs and Newman 2005). This movement, which leads to the appearance of new forms (emergent properties), must, on the one hand, satisfy the constraints imposed by the activity of the maternal and zygotic genes and on the other hand should proceed according to the governing physical mechanisms, which exert forces on the cells (causal processes). The laws of chemical transformation also dictate the direction of change. Time-dependent physical processes are triggered (i.e., shape changes) that steer the system into new equilibrium (or steady) state, which corresponds to a new shape, again temporary. The altered shape of the embryo, or portion thereof, may in turn influence the course of subsequent development. This process is called a "protean[13] process" (Forgacs and Newman 2005) and I call it NC-plasticity.

During the later stages of embryogenesis, the body, as a whole, becomes more structurally complex and functionally integrated. This functional integration corresponds to a state of equilibrium (end of development). Forgacs and Newman (2005) suggest that "basic physical mechanisms [constraints] become correspondingly less applicable to an understanding of the changes in the shape and form of the entire organism as development proceeds."

Therefore, if we consider NC-plasticity as a protean ability depending on the early constraints during morphogenesis, other boundaries could be ascribed to development than the one with the BC-plasticity. Development ends when limits of these basic physical and molecular constraints are reached, when emergent properties decrease in the face of simple causal properties of morphological process, leading to the end of the morphological process and to the beginning of physiological process. Equilibrium is reached when phenotypic change might only be depicted by reaction norms and phenotypic plasticity (the genetic conception of plasticity).

Conclusion

I suggested at the beginning of the article that two conceptions of plasticity should be distinguished: a "genetic conception of plasticity" which is linked to a description of the reaction norm and to the rediscovery of Mendel's laws; and a "developmental conception of plasticity," which is based on the theory of epigenesis and on morphogenesis studies. With the Modern Synthesis, attention has been focused on the genetic conception of plasticity leading to some clarifications concerning the genotype–environment interaction. With the advent and growth of EvoDevo debates, the distinction between the two conceptions has tended to disappear, leading to a merged conception that I have called BC-plasticity. I have shown that this broad conception has been used in order to answer what Evo-Devo biologists have called "Wallace's Challenge"

[13] In reference to the Greek myth of Proteus who can foretell the future, but will change his shape to avoid having to; he will answer only to someone who is capable of capturing him. From this feature of Proteus comes the adjective protean: "capable of assuming many forms," "versatile," or "flexible".

(West-Eberhard 2003, p. 11). I have shown that Wallace's statement is actually not a challenge but an "awareness program" for developmental biologists. Wallace highlighted the fact that developmental biology may address a different perspective than what the MS was doing and may focus specifically on the morphological processes of organisms (the distinction between the two perspectives is illustrated by the optical illusion sketch of the old and the young lady). A definition of development as a process that never stops is a consequence of a merge between the two conceptions of plasticity within BC-plasticity. I have shown that another perspective was possible by focusing on the developmental conception of plasticity (NC-plasticity). I have compared (Table 1) two distinct views (the broad conception—BC-plasticity—and the narrow conception—NC-plasticity). BC-plasticity suggests a definition of development in a life-cycle perspective as a law-like process and it is based on the traditional analysis of environment–genotype interactions. This perspective, which claimed to challenge the Modern Synthesis, is finally quite similar. It remains focused on the signals interaction itself instead of taking into account the processes also. The NC-plasticity suggests an alternative conception of development, based on the older understanding of the notion, which today is understood as a feature of morphological process. Because this conception focuses more on the variation of the genotype–environment interaction over time than on the signals' interaction itself, it gives another, more historical view of development. Following Wallace's advice, I conclude in favor of the thesis that development is determined by the boundaries of the morphological process, which depends on NC-plasticity. Further studies on the causes of variation in the input interaction (in the vein of Salazar-Ciudad or Newman's studies) may provide good indications for the identification of these developmental boundaries. It is high time to have a closer look at the young lady!

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References

Adams MB (1980) Sergei Chetverikov, the Koltsov Institute, and the evolutionary synthesis. In: Mayr E, Provine WB (eds) The evolutionary synthesis: perspectives on the unification of biology. Harvard University Press, Cambridge, MA, pp 242–278

Aristotle (1999) In: Waterfield R (trans), Bostock D (ed) Physics. Oxford: Oxford University Press

Bendall DS (ed) (1983) Evolution: from molecules to men. Cambridge University Press, Cambridge, pp 273–285

Bolker J (1995) Model systems in developmental biology. BioEssays 17(5):451–455

Bradshaw AD (1965) Evolutionary significance of phenotypic plasticity in plants. Adv Genet 13:115–155

Brakefield P, Gates J, Keys D, Kesbeke F, Wijngaarden PJ, Montelro A, French V, Carroll SB (1996) Development, plasticity and evolution of butterfly eyespot patterns. Nature 384:236–242

Buss L (1987) The evolution of individuality. Princeton University Press, Princeton NJ

Cavalli-Sforza LL (1974) The genetics of human populations. Sci Am 231(3):80–89

Coleman W (1980) Morphology in the Evolutionary Synthesis. In: Mayr E, Provine WB (eds) The evolutionary synthesis: perspectives on the unification of biology. Harvard University Press, Cambridge, pp 174–180

Cudworth R (1678) True intellectual system of the universe. Richard Royston, London

Diggle PK (1993) Developmental plasticity, genetic variation, and the evolution of andromonoecy in *Solanum hirtum* (Solanaceae). Am J Bot 80(8):967–973

Diggle PK (1994) The expression of andromonoecy in *Solanum hirtum* (Solanaceae): phenotypic plasticity and ontogenetic contingency. Am J Bot 81:1354–1365

Dobzhansky T (1937/1951) Genetics and the origin of species, 3rd edn. Columbia University Press, New York

Dobzhansky T, Boesiger E (1983) In: Wallace B (ed) Human culture: a moment in evolution. Columbia University Press, New York

Driesch H (1928) Philosophie des Organischen. Quelle & Meyer, Heidelberg

Duchesneau F (1998) Les modèles du vivant de Descartes à Leibniz. Vrin, Paris

Dunn LC (1965) A short history of genetics: the development of some of the main lines of thought. McGraw-Hill, New York, pp 1864–1939

Dupont J-C, Schmitt S (2004) Du feuillet au gène: Une histoire de l'embryologie moderne, fin XVIIIe-XXe siècle. Rue d'Ulm, Paris

Epel D (2009) Ecological developmental biology: integrating epigenetics, medicine, and evolution, chap. 1. MIT Press, Cambridge

Fisher RA (1918) The correlation between relatives on the supposition of mendelian inheritence. Trans R Soc Edinb 52: 399–433

Forgacs G, Newman SA (2005) Biological physics of the developing embryo. Cambridge University Press, New York

Fusco G, Minelli A (2010) Phenotypic plasticity in development and evolution: facts and concepts. Phil Trans R Soc B 365(1): 547–556

Gilbert S (2000/2010) Developmental biology, 9th edn (also 6th edn for chap 22) Sinauer Associates, Sunderland

Gilbert S, Epel D (2009) Ecological developmental biology: integrating epigenetics, medicine, and evolution. Sinauer Associates, Sunderland

Gotthard K, Nylin S (1995) Adaptive plasticity and plasticity as an adaptation: a selective review of plasticity in animal morphology and life history. Oikos 74(1):3–17

Gould SJ (1977) Ontogeny and phylogeny. Harvard University Press, Cambridge

Gupta AP, Lewontin RC (1982) A study of reaction norms in natural populations of *Drosophila pseudoobscura*. Evolution 36:934–948

Hall BK (1999) Evolutionary developmental biology, 2nd ed edn. Kluwer, Dordrecht

Hall BK (2003) Unlocking the black box between genotype and phenotype: cell condensations as morphogenetic (modular) units. Biol Philos 18:218–243

Hall BK, Olson WM (2007) Kewords and concepts in evolutionary developmental biology. Harvard University Press, Cambridge
Hall BK, Pearson RD, Müller GM (2004) Environment, development, and evolution: toward a synthesis. MIT Press, Cambridge, MA
Hamburger V (1980) Embryology. In: Mayr E, Provine WB (eds) The evolutionary synthesis. Harvard University Press, Cambridge, MA, pp 96–112
Hoverman JT, Relyea RA (2007) How flexible is phenotypic plasticity? Developmental windows for trait induction and reversal. Ecology 88(3):693–705
Ioannidis S (2008) How development changes evolution: conceptual and historical issues in evolutionary developmental biology. Biol Philos 23(4):567–578
Johannsen WA (1911) The genotype conception of heredity. Am Nat 45:129–159
Laplane L (2011) Stem cells and the temporal boundaries of development: toward a species-dependent view. Biol Theory doi: 10.1007/s13752-011-0009-z
Larsen E (2004) A view of phenotypic plasticity from molecules to morphogenesis. In: Hall B, Pearson R, Müller G (eds) Environment, development, and evolution: toward a synthesis. MIT Press, Cambridge, MA, pp 117–124
Laubichler MD, Maienschein J (2007) From embryology to Evo-Devo: a history of developmental evolution. MIT Press, Cambridge, MA
Lauder GV (1982) Introduction. In: Russell ES (ed) Form and function: a contribution to the history of animal morphology. University of Chicago Press, Chicago, pp xi–xlv
Lerner IM (1954) Genetic homeostatis. Wiley, New York
Lewontin R (2001) Gene, organism and environment: a new introduction. In: Oyama S, Griffiths P, Gray R (eds) Cycles of contingency: developmental systems and evolution. MIT Press, Cambridge, MA, pp 55–58
Malpighi M (1673) Dissertatio epistolica de formation pulli in ovo. J. Martyn, London
Minelli A (2011) Animal development: an open-ended segment of life. Biol Theory. doi: 10.1007/s13752-011-0002-6
More H (1659/2011) The immortality of the soul, so farre as it is demonstrable from the knowledge of nature and the light of reason. Eebo Editions, Proquest
Morgan TH (1934) Embryology and genetics. Colombia University Press, New York
National Research Council (NRC) (1985) Models for biomedical research, a new perspective. A report by the committee on models for biomedical research. National Academy Press, Washington
Newman SA, Bhat R (2008) Dynamical patterning modules: physico-genetic determinants of morphological development and evolution. Phys Biol 5(1):0150580
Nijhout H (1991) The development and evolution of butterfly wing patterns. Smithsonian Institution Press, Washington
Oyama S, Griffiths PE, Gray RD (2003) Cycles of contingency: developmental systems and evolution. MIT Press, Cambridge, MA
Pener MP (1991) Locust phase polymorphism and its endocrine relations. In: Evans P (ed) Advances in insect physiology, vol 23. Academic Press, London, pp 1–79
Piersma T, Lindström Å (1997) Rapid reversible changes in organ size as a component of adaptive behaviour. Trends Ecol Evol 12(4):134–138
Pigliucci M (1997) Ontogenetic phenotypic plasticity during the reproductive phase in *Arabidopsis thaliana* (Brassicaceae). Am J Bot 84(7):887–895
Pigliucci M (2001) Phenotypic plasticity: beyond nature and nurture. Johns Hopkins University Press, Baltimore
Pigliucci M, Müller G (2010) Evolution: the extended synthesis. MIT Press, Cambridge, MA
Roe SA (1979) Rationalism and embryology: caspar Friedrich Wolff's theory of epigenesis. J Hist Biol 12(1):1–43
Salazar-Ciudad I, Newman SA, Sole RV (2001) Phenotypic and dynamical transitions in model genetic networks I. Emergence of pattern and genotype-phenotype relationships. Evol Dev 3(2):84–94
Salazar-Ciudad I, Jernvall J, Newman SA (2003) Mechanisms of pattern formation in development and evolution. Development 130(10):2027–2037
Sansom R, Brandon RN (2007) Integrating evolution and development: from theory to practice. MIT Press, Cambridge, MA
Sarkar S (1999) From the reaktionsnorm to the adaptive norm: the reaction norm, 1909–1960. Biol Philos 14:235–252
Scheiner SM (1993) Genetics and evolution of phenotypic plasticity. Annu Rev Ecol Evol Syst 24:35–68
Schlichting CD (1986) The evolution of phenotypic plasticity in plants. Annu Rev Ecol Evol Syst 17:667–693
Schlichting CD, Smith H (2002) Phenotypic plasticity: linking molecular mechanisms with evolutionary outcomes. Evol Ecol 16:189–211
Schmalhausen II (1949) In: Dordick I (trans), Dobzhansky T (ed) Factors of evolution. Blakiston, Philadelphia
Spemann H, Mangold H (1924) Induction of embryonic primordial by implantation of organizers from different species. In: Willer BH, Oppenheimer JM (eds), Foundations of experimental embryology. New York: Hafner, pp 144–184
Stearns S, de Jong G, Newman B (1991) The effects of phenotypic plasticity on genetic correlations. Trends Ecol Evol 6(4): 122–126
Stent GS (1985) Thinking in one dimension: the impact of molecular biology on development. Cell 40(1):1–2
Sultan SE (1987) Evolutionary implications of phenotypic plasticity in plants. Evol Biol 21:127–178
Sultan SE (2000) Phentotypic plasticity for plant development, function and life history. Trends Plant Sci 5(12):537–542
Van der Weele C (1993) Metaphors and the privileging of causes. Acta Biotheor 41(12):315–327
Via S, Gomulkiewicz De, Jong G, Scheiner SM, Schlichting CD, Van Tienderen PH (1995) Adaptative phenotypic plasticity: consensus and controversy. Trends Ecol Evol 10(5):212–217
Vogt O (1926) Psychiatrisch wichtige Tatsachen der zoologisch-botanischen Systematik. J Psychol Neurol 101:805–832
Waddington CH (1940) Organisers and genes. Cambridge University Press, Cambridge
Wallace B (1986) Can embryologists contribute to an understanding of evolutionary mechanisms? In: Bechtel W (ed) Integrating scientific disciplines. Nijhoff, Dordrecht, pp 149–163
West-Eberhard MJ (1989) Phenotypic plasticity and the origins of diversity. Annu Rev Ecol Evol Syst 20:249–278
West-Eberhard MJ (1992) Behavior and evolution. Molds, molecules and metazoa: growing points in evolutionary biology. Princeton University Press, Princeton, pp 57–75
West-Eberhard MJ (2003) Developmental plasticity and evolution. Oxford University Press, Oxford
Williams G (1996) Adaptation and natural selection: a critique of some current evolutionary thought. Princeton science library edn. Princeton University Press, Princeton
Wolff CF (1759) Theoria generationis. Litteris Hindelianis, Halae ad Salam
Woltereck R (1909) Weitere experimentelle Untersuchungen über Artveränderung, speziel über das Wesen quantitativer Artunterschiede bei Daphnien. Verhandlungen der deutschen zoologischen Gesellschaft 19:110–173
Wright S (1920) The relative importance of heredity and environment in determining the piebald pattern of Guinea-Pigs. Proc Nat Acad Sci USA 6(6):320–332